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SMALL TURBINE-TYPE FLOWMETERS FOR LIQUID HYDROGEN

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Small Turbine-Type Flowmeters for Liquid Hydrogen

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Statistical data are presented on the reproducibility and linearity of turbine-type sensors, in 2-cm to 5-cm sizes, with various types of bearings. Design principles, installation practices, and inspection procedures are suggested that are conducive to reliability. The efficacy of room-temperature calibration with water or high-pressure nitrogen gas is also considered. Actual calibration in liquid hydrogen is required to identify meters of good quality (calibration reproducibility with less than 0.3% probable error) and to establish the mean calibration curve with minimum error. Designs operating at fluid velocities up to 30 m/sec can yield a calibration factor that is constant to 0.5% over a 10:1 flow range.

INTRODUCTION

The turbine-type flowmeter has been popular for measuring the flow of liquid hydrogen in rocket propulsion research and development because of its compactness, simplicity of installation, and tendency to integrate several forms of transverse velocity distributions in the approach piping.

The most common form of this meter uses a multi-bladed axial-flow rotor whose rotational speed is measured by means of an electromagnetic pickup mounted on the outer surface of the casing, to count pulses generated by blade passage. This paper will be concerned solely with this type of primary element, which will be termed the meter for brevity, and will not be concerned with the electronic frequency-measuring instrumentation.

In the idealized, energy-conservative (nondissipative) case, the rotational speed will be directly proportional to volumetric flow rate in the upstream piping, the factor of proportionality depending principally on the blade angle, the annular area of the blade passageway, the radial distribution of velocity, and various geometric parameters such as blade solidity (chord-to-spacing ratio), blade-tip and rotor clearances, approach-hub shape, and wall smoothness. The meter may then be assigned a calibration factor C , the pulses per unit volume, which, in the calibration act, is actually the measured number of pulses per unit time, N , divided by the independently-measured volumetric flow rate \dot{V} . Ideally, the calibration factor would be constant at all flow rates.

In the practical case, where dissipation is present, the calibration factor drops off at lower flow rates, because of the increasing dominance of mechanical friction and other drag forces. The curve of calibration factor C vs pulse frequency N may have any of the shapes shown in Fig. 1, depending on the ratios between driving and retarding torques. The driving torque available to maintain rotor speed is proportional to dynamic pressure $\rho v_a^2/2$, where ρ is fluid density and v_a is some mean linear velocity of the fluid in the blade annulus. Retarding fluid-friction torques will increase with fluid viscosity and with some power (between 1 and 2) of

fluid velocity. Retarding bearing torques will be proportional to the coefficient of bearing friction. Mechanical bearing friction is particularly dominant in metering liquid hydrogen because of the liquid's low density and low kinematic viscosity.

The subject of the balance between driving and retarding torques has been treated by several investigators^{1,2,3}, although not with specific direction toward liquid hydrogen. Lee and Karlby¹ show that the left-hand end of the curves of Fig. 1 is associated with the low Reynolds No. regime, whereas the right-hand end is associated with the high Reynolds No. regime. The right-hand asymptote of the curves is a horizontal line because then both dynamic pressure and fluid friction vary substantially as the square of velocity. The effect of bearing friction is further to reduce the value of C at low fluid velocities. In past experience⁴, the drop in C at some given relatively-low velocity has always been greater in liquid hydrogen than in a denser fluid such as water.

A particular meter is characterized principally by its asymptotic calibration factor C_m . Other meter characteristics that interest a user are related to (1) the stability (reproducibility) of calibration factor $C(\dot{V})$ with time and (2) the flatness (linearity) of the calibration curve, i.e., the extent to which $C(\dot{V}) \approx C_m$ over an appreciable span of flow rate .

Published analyses^{1-3,5-9} of the turbine-type meter have contributed to an understanding of its operation and have provided the means of estimating the effects on the calibration factor of changes in operating conditions. Thompson and Grey^{8,9} have provided a comprehensive summary of many factors of meter performance, and have demonstrated that C_m could be predicted well if boundary conditions were adequately defined.

Actual reported calibration experience with liquid hydrogen is limited. Deppe¹⁰ has reported on a 20-cm meter and a 45-cm meter, including some data taken at the Los Alamos Scientific Laboratory Cryogenic Facility at Jackass Flats, Nevada. (Size designations refer to the nominal pipe diameter.) Mortenson and Wheelock¹¹, in a report on mass flowmeters, include a volumetric calibration of a 7.5-cm turbine-type meter. However, the only reports that contain sufficient statistical information to bear on points (1) and (2) above are those by Bucknell¹²⁻¹⁴, on 7.5-cm meters, and by Minkin⁴, et al on 2-cm to 5-cm meters. The present paper extends the latter work on small meters and abstracts some of it. The extension of work relates principally to a study of the role of the bearing and to an exploration of the advantages of operating, in hydrogen, at higher rotational speeds and liquid velocities than would ordinarily be considered safe maxima for water service.

To facilitate comparison of meters of different sizes, the independent variable will usually be chosen as the average linear velocity v in the unobstructed upstream piping, instead of the more conventional quantity N , which is approximately proportional to v for a given meter.

TESTS

Facility

All tests were conducted in the NASA-Lewis calibration facility^{15,16} for liquid-hydrogen meters. Some minor improvements have been made since the earlier reports. The primary reference standard provides a continuous record of mass displacement of fluid in the supply tank by recording the change in buoyant force on a long, cylindrical float suspended in the tank. A secondary working standard is a series of hot-wire probes located at fixed levels in the tank; these, connected to appropriate timing systems, provide a measure of incremental volume displacements of the gas-liquid interface. Flow is produced by continuous flow of pre-cooled helium gas, under pressure, into the space above the gas-liquid interface. Flow rates up to 10 liters/sec were used in the present series of tests; the highest flow rate used in any test was always sufficient to define the value of C_m . The test meters are bathed in their own effluent liquid, so that heat losses are negligible. Densities in the tank and in the test section are determined to a probable error of 0.02% by means of platinum-resistance thermometers¹⁷; independent check against a buoyant-force method had confirmed the accuracy of the procedure^{15,16}.

Continuously monitored and recorded readings of suppressed-zero frequency meters connected to each of the meters being tested confirms that flow rate is constant during the duration of a run. Records of an on-the-fly electronic counter that prints out the accumulated pulses every 10 seconds, and of the primary mass-displacement device, provide subsequent independent confirmations that flow rate had been constant.

Procedure

A calibration point is taken by pressurizing the supply tank, establishing constant flow rate from the supply tank to the receiving tank, and then making measurements of mass and volume displacement, pulse rate, and pulse accumulation for a period on the order of 100 seconds. Then, flow is reversed, and the contents of the receiving tank returned to the supply tank in preparation for the next point. Thus, the meter is run backwards, at slow speed, between successive points. Experience shows that the order in which points are taken along the calibration curve does not affect the value of C obtained. A complete calibration, including incidental operations such as cooldown, entails about two hours of running time for the meter.

Accuracy

For purposes of establishing reproducibility, the probable error (e_p) of a single observation, that is introduced by the calibration facility and operating technique, is estimated to be less than 0.06% in the upper half of the flow-rate range for any meter, increasing to about twice this value at the lowest flow rate of the range. Because of the smoothing introduced by the curve-fitting act, the contribution of the calibration system and technique to the e_p of determining C_m is estimated to be less than 0.03%.

For purposes of establishing absolute accuracy, as required in comparing calibrations performed in different test facilities, the e_p of a single observation may be taken as 0.25% because invariant, but uncertain, errors of the facility must be included.

The meter itself adds additional random errors. The resultant distribution of errors is usually of a truncated Gaussian form, and experience shows that at least 95% of the errors will be less than $2e_p$.

Test Meter Arrangement

Two test meters, in series, separated by flow-straightening sections, are tested at a time. Comparison between the two meters will serve to reveal those mistakes in the calibration operation which would produce similar aberrations on both graphs of $C(N)$. The arrangement for the 2.5-cm meters is shown in Fig. 2. Flow-straightening precautions are more elaborate than those in earlier tests⁴ because the earlier tests had indicated a slight systematic difference in C_m between upstream and downstream positions of at least one model of meter. Each straightener was a bundle of 13 0.25mm-wall, 7.5mm diam. tubes, 75mm long.

Test Meters

Two models of 2.5-cm (nominal 1-inch) meters and one model of 4-cm (nominal 1.5-inch) meter were tested to study reproducibility and the influence of the bearings. The 4-cm meter was the same model as reported on previously⁴. Another single 4-cm meter resembling a previously-tested model was included because it had an exceptionally reproducible C_m and provided a check on the reliability of the calibration procedure. The 4-cm meters were standard water-service types; the 2.5-cm meters were specifically for liquid-hydrogen service. Some characteristics of these meters are listed in Table I.

Bearings

It has been known for some time^{18,19,20} that ball bearings with glass-filled polytetrafluoroethylene (PTFE) retainers were very desirable for liquid-hydrogen service. However, retainers for such small bearings as used in the 2.5-cm meters had not been available until the initiation of the present series of tests. Accordingly, prior work^{4,15,16} had all been performed with full-complement, unshielded bearings; performance had been quite satisfactory.

The type Bd, E, and F meters procured for the new tests were furnished with shielded ball bearings having retainers of a proprietary form of glass-filled PTFE. After the type F meters were tested in the as-received condition, the bearings in some meters were replaced with full-complement, unshielded bearings for comparative tests.

At about the same time, other filled-PTFE material became available, from which journal bearings could be fabricated. The substitution of journal bearings for ball bearings was convenient only in the case of the type A meters. Although four different proprietary mixes of material were tried, results were not significantly different among the various mixes, perhaps because there were only a few trials of each; all results on journal bearings are therefore lumped in a common category. The bearing type will be identified by a suffix following the meter-type designation, as follows:

- F full-complement, unshielded radial ball-bearing
- R shielded radial ball bearing with glass-filled PTFE retainer

-J filled-PTFE journal bearing, 1 mm wall thickness, with one of the following fillers: (1) 25% glass, (2) 15% glass, (3) 10% organic polyamide, (4) 60% bronze (this material appeared to produce slightly poorer performance than the others, but not so strongly as to warrant separate consideration).

All metallic bearing parts were of AISI 440C stainless steel. The fit of shafts in the bores was quite loose, so that axial motion of the rotor was possible. In type A meters, thrust was taken by the rounded end of the rotor shaft, bearing on a steel plate. In types B, E, and F meters, thrust was taken by the deep-groove ball bearing.

Number of Calibrations

Table II lists the number of useful calibrations performed on the various designs of meters. A few runs, which are discussed later under Reliability, were rejected because no meaningful values of C could be derived from them.

RESULTS AND DISCUSSION

To provide a common basis for comparison of meters of different sizes, the abscissa of the calibration curve will generally be taken as the mean linear velocity v in the unobstructed upstream piping for which the meter is designed. The velocity v is substantially proportional to N and to \dot{V} . The reasons for this choice of independent variable are practicality and convenience--most piping systems are designed with linear velocity as a criterion. To the meter designer, a preferable criterion

would be the mean linear velocity in the blade annulus; this is derivable from the data in Table I.

Meter characteristics of interest to a user may be itemized explicitly as follows:

(1) The constancy (reproducibility) of C and C_m that may be expected for a given meter, with continued use. Reproducibility is always poorer at the lower end of the velocity range.

(2) The shape of the calibration curve $C(v)$ and its possible variation among a set of meters of the same type.

(3) The lowest velocity $v_{\min,1}$ at which $C(v)$ may be expected to remain reproducible to some stated, acceptably small tolerance, for a single meter of a set of the same type.

(4) The lowest velocity $v_{\min,2}$ at which $C(v)$ may be expected to differ from C_m , for all $v \geq v_{\min,2}$, by some stated, acceptably small amount. Thereby, the single number C_m may conveniently be used as the calibration factor for the meter over the entire range $v \geq v_{\min,2}$.

(5) The maximum velocity v_{fs} that may be assigned as the full-scale range of a set of meters of a given type. Presumably, $C(v_{fs})$ is equal to C_m . The chosen value of v_{fs} (or corresponding N_{fs}) will represent a compromise between bearing life and pressure loss on the one hand, because these are adversely affected by higher v_{fs} , and the useful range on the other hand, because this is increased by higher v_{fs} .

Useful range is either ($v_{\min,1}$ to v_{fs}) or ($v_{\min,2}$ to v_{fs}). It is between $v_{\min,1}$ and v_{fs} if accuracy is the principal consideration, because $v_{\min,1}$ is determined by reproducibility. Useful range is between $v_{\min,2}$

and v_{fs} if convenience is the principal consideration, because then the meter is said to have a constant calibration factor. The ratio $v_{fs}/v_{min,2}$ ($= N_{fs}/N_{min,2}$) has been termed the linear range in prior publications⁴.

(6) The ability to predict C and C_m for liquid hydrogen, by performing calibrations with a different fluid that is more convenient to use.

In the following presentation of results on statistical dispersion, three levels of complexity are to be distinguished:

(1) The dispersion of points about a single calibration curve. For the approximately 150 calibrations analyzed here, the average e_p was 0.07%, and 90% of the calibrations had $e_p \leq 0.15\%$.

(2) The dispersion of calibration curves for a single meter, about some mean calibration curve.

(3) The dispersion of calibration curves for a set of meters of one type. This comparison is meaningful only if the ordinates of each curve are expressed in the nondimensional form C/C_m .

Reproducibility of C_m

Repeated calibrations of a given meter will yield a mean (most probable) value of C_m and a maximum deviation $|\Delta C_m|_{max}$ from that mean. Table III lists the value of this quantity, averaged over all meters of a given type, expressed as percent of C_m . Earlier work⁴ yielded a value on the order of 0.5% for three types of meters (the quantity C_{nfs} in the earlier work is equal to C_m).

The number of repeated calibrations of a single meter ranged from 2 to 13 for A-J types, and was close to the average number listed in Table II for the other types. For purposes of computing deviations from a mean, it was considered that a new meter had been created whenever a meter was disassembled and re-assembled to change bearings, so that the meter had a new C_m . With repeated calibration, entailing a total meter usage generally ranging between 8 and 26 hours, there was no evidence of a progressive increase in the random scatter of C_m , that would imply mechanical deterioration. Nor was there such evidence at the lower end of the useful velocity range.

The probable error of knowledge of C_m for a given meter is one half of the numbers given in Table III. The lowest value of e_p derivable from Table III, that for the type Bd meter, is comparable to the estimated e_p of the calibration operation. This is not an independent finding, but merely an illustration of how the e_p of the calibration technique was arrived at; namely, by assuming it to be near the lower bound of the e_p obtained in the calibrations of meters of high quality.

Reproducibility of C for a Single Meter

Repeated calibrations of a single meter will not yield the same calibration curve each time. The curves will scatter by some amount, which will increase as fluid velocity drops. The envelope of all calibration curves of a single meter may have the appearance shown in the insert in Fig. 3. The value of the maximum dispersion of C , as defined in the insert, has been determined for each meter, but this data

is too voluminous to present. Instead, Fig. 3 presents the average value of $|\Delta C|_{\max}/C_m$ for each of the types of meters listed in Table II.

The e_p of C , in percent, is one half of the ordinates of Fig. 3. Thus, the curves provide a means of establishing the abscissa $v_{\min,1}$ beyond which the e_p of C for a single meter will be less than any chosen amount. Figure 3 helps to answer the question: given the most probable calibration of a given meter, how may other calibrations of the same meter differ?

Shape of $C(N)$ or $C(v)$

Figure 4a shows the shape of C/C_m (derived from mean curves such as shown in the inset of Fig. 3) that may be expected, on the average, for each of the meter types listed in Table II. The intersections of the curves with a horizontal line at any selected ordinate provide the abscissas $v_{\min,2}$ above which C will deviate by less than the selected amount from its asymptotic value C_m . The comparison of curve shapes provides a statistical basis for estimating the relative merits of different meter designs in establishing a minimal value of $v_{\min,2}$. For a given geometric design of meter, there was no significant difference due to the type of bearing used.

The ordinates of the mean curves shown in Fig. 4a are subject to random variation. If all calibrations of all meters of a given type are plotted on the same sheet of paper, using the nondimensional ordinate C/C_m , the envelope of these curves (inset, Fig. 4b) encloses a region in which one has a high probability of finding the calibration-curve shape

of another meter of the same type. Figure 4b shows the maximum dispersion $|\Delta(C/C_m)|_{\max}$ of at least 90% of all calibration curves obtained on each type of meter listed in Table II. At low velocities, the ordinates in Fig. 4b are higher than those in Fig. 3 because (1) Fig. 4b presents extreme values of the dispersion, whereas Fig. 3 presents average values of the maximum dispersion and (2) Fig. 4b includes the effect of manufacturing variations among the several meters of one type, whereas Fig. 3 represents a single, average meter of that same type. The more useful and realistic e_p of C/C_m is one half the ordinate values given in Fig. 4b.

Useful Range

Two reasonable criteria for determining v_{fs} are bearing life and pressure drop. The statistical determination of bearing life, in controlled experiments, has not yet been made. The only information relevant to this subject is (a) the record of accumulated service (8 to 26 hr.) on the test meters as reported under Reproducibility of C_m , (b) earlier work⁴ of similarly limited nature, and (c) the manufacturer's designated nominal full-scale meter range, presumably influenced by the bearing manufacturer's conventional ratings.

Pressure drop varied accurately as the square of the velocity. Only about ten percent of this drop occurs across the rotor itself; the remainder is due to the straighteners, bearing supports, and casing. Table IV lists the value of linear velocity and of corresponding rotational speeds, at which stated pressure drops occur across the meter. The nominal

full-scale speed is also listed. If any one of these velocities is taken as v_{fs} , its combination with the chosen $v_{min,1}$ (from Fig. 3) or $v_{min,2}$ (from Fig. 4), whichever is preferred, will define the useful range of the meter.

For example, the useful range ratio $v_{fs}/v_{min,1}$, based on 3.5 N/cm^2 ($\approx 5 \text{ psi}$) pressure drop at v_{fs} , and on $e_p = 0.22\%$ (Fig. 3) is on the order of 5 for type A meters and 10 for the other types listed in Table IV. The linear range $v_{fs}/v_{min,2}$, based on the same pressure drop and on $(C/C_m) \geq 0.995$ (Fig. 4) is on the order of 12 for type F meters and 5.5 for the other types.

As a rule of thumb, the same pressure drop will occur at 30 m/sec in liquid hydrogen as occurs at 8 m/sec in water.

Calibration With Other Fluids

Since C_m presumably is independent of mechanical bearing friction, and is reached in the turbulent-flow regime, its value for some other fluid should be the same as its value for liquid hydrogen (LH_2) if one can maintain the same velocity-profile shape and magnitude at the leading-edge of the blades, and the same ratio of driving torque to fluid-friction torque, and if correction is made for thermal expansion. Table V lists the density and kinematic viscosity of fluids that have been used for simulation. Water has been common because of its convenience, although its properties do not match those of liquid hydrogen. High-pressure gaseous nitrogen (GN_2) can provide a close approximation to both density and kinematic viscosity, although large quantities of gas are required.

The thermal-expansion correction and the effects of viscosity have both been treated in the published literature^{1,6,21}. An additional small correction for blade-tip clearance and boundary-layer effects has also been computed²¹. Calibration with high-pressure N_2 has proved more effective than a water calibration, in predicting C_m , in 6 out of 9 experiments²¹. The high-pressure N_2 calibration yields an e_p of 0.4% in predicting C_m and of about 2.5% in predicting C at 20 percent of nominal full-scale range²¹.

A few meters used in the current tests were calibrated in water. Figure 5 summarizes the present and prior results^{4,21} of simulations on small meters. The length of the bar represents the estimated probable error of the determination, which includes the errors of the calibration facilities.

Figure 6 compares the shapes of the calibration curves of two types of flowmeters in water. The shape of the curve for the type E meter is markedly different from the curve shown in Fig. 4a for the same meter in liquid hydrogen.

The wide dispersion of the ratio $C_m(H_2O)/C_m(LH_2)$ shown in Fig. 5, and the disparity between H_2O - and LH_2 -calibration curve shapes for the type E meter (Figs. 4 and 6) suggest that there may be distinct differences in velocity profile at the blades, for the two fluids, that are as important as the temperature difference in establishing the ratio. The smaller dispersion of the ratio $C_m(GN_2)/C_m(LH_2)$, where density and Reynolds No. are closely simulated, and the nearness of the ratio to the

value predicted by thermal-expansion considerations alone, lend some credence to this suggestion.

Blade-Tip Clearance

Earlier work⁴ had suggested that a smaller clearance between blade tips and casing might lower the value of $v_{\min,2}$. This thesis was tested on a type A meter. The blade-tip radius on this meter was substantially equal to the radius of the entrance and exit portions of the meter body; however, the casing in the vicinity of the blades was of larger radius, for a length of 46 mm (about 6 blade lengths), producing a tip clearance of 1.3 mm. Insertion of a cylindrical sleeve into this expanded area reduced the tip clearance to 0.13 mm. The value of C_m was thereby increased from 87 pulses/liter to 100 pulses/liter, demonstrating that there had been considerable bypassed flow. The graph of C/C_m vs v was changed as shown in Fig. 7, showing a reduction in $v_{\min,2}$.

Reliability

A preliminary test for identifying a defective meter is to blow dust-free air through the meter with just enough velocity to induce spinning of the rotor, and then to observe how the rotor comes to rest when blowing is terminated abruptly; the rotor should decelerate smoothly and finally oscillate with decreasing amplitude, due to magnetic coupling with the pickup coil, until it comes to rest. Failure to oscillate is generally indicative of a dirty meter or defective bearing. All meters that passed this test provided usable data in the experiments that have been described here.

However, not every calibration run was usable. Occasionally, data in a single calibration scattered so badly that it was impossible

to establish a clearly-defined asymptote or to draw a meaningful calibration curve. This happened 5 out of 178 times. In two of these instances, prior and subsequent calibrations of the same meter, a few days or hours apart, were satisfactory. In two other instances, the bad calibrations were the first ones performed after installation of new bearings.

On other occasions, data in a single calibration scattered so badly that e_p exceeded 0.3%, although a poor estimate of C_m could be made. This happened 4 out of 178 times. One of these instances followed one of the bad calibrations, after installation of new bearings, that was mentioned above; in the other three instances, immediately prior and subsequent calibrations were satisfactory.

The effect of the act of disassembly and reassembly to change bearings was tested on two type F meters, where three such sets of operations were performed: -R to -F to -R to -R. There were about five calibrations after each change. The successive values of $|\Delta C_m|_{\max}/C_m$ for each group of calibrations were 0.16, 0.21, 0.8, 1.2% for one meter and 0.12, 0.16, 0.34, 0.16% for the other. These values suggest that there was progressive deterioration in bearing cleanliness, fit, or alignment with most successive assembly operations. Data for the last two groups of calibrations have therefore been omitted in preparing Figs. 3 and 4.

In general, those meters that produced one relatively-poor calibration (relatively large e_p of a single observation) also had a relatively higher e_p of C_m among all the calibrations. Conversely, meters, like the type Bd meter, that produced at least four consecutive

calibrations with low e_p of a single observation, continued to show this good performance in succeeding calibrations.

CONCLUSIONS

Table III indicates that it is now possible to obtain meters whose asymptotic calibration factor is reproducible to an e_p on the order of 0.1% at full scale. The worst value of e_p is only 0.2%. Figure 3 provides a means of determining the e_p at lower velocities or, conversely, of determining the $v_{min,1}$ corresponding to a selected e_p . In type A meters, ball bearings yield slightly lower dispersion than journal bearings at low flow rates. In type F meters, there is no distinctive difference between full-complement ball bearings and those with filled-PTFE retainers.

Figure 4a demonstrates the diversity of mean curve shapes encountered with different meter designs, but also shows that bearing type has negligible effect on mean curve shape. Comparing Figs. 4 and 6, it appears that a water calibration can not always be relied on to provide the calibration-curve shape in liquid hydrogen.

Figure 4b shows the double-amplitude of the probable-error band that must be ascribed to each of the mean curves of Fig. 4a. There is negligible difference in band width due to bearing type, in both cases (types A and F) where comparisons are possible. The apparent superiority of type Bd at $v < 3$ m/sec is to be attributed, at least in part, to the fact that only one meter was tested.

Bearing life, which has yet to be studied, may be the one strong determinant of the superiority of one type of bearing.

Assuming that bearing life would be adequate, and assuming a pressure drop in liquid hydrogen that would be comparable to that which is common in water service, useful range ratios on the order of 10:1 could be achieved with $e_p = 0.25\%$ and $C/C_m \geq 0.995$. The non-unity value of C/C_m is not an error--just an inconvenience.

Figure 5 suggests that water calibrations are unlikely to yield values of C_m with values of e_p as small as those derivable from a liquid-hydrogen calibration (Table III).

The larger values of e_p in Fig. 5, when compared with the values derivable from Fig. 3, also show that absolute inaccuracy may be four times the nonreproducibility.

Small blade-tip clearance, which is feasible in a clean fluid like liquid hydrogen, appears to improve meter performance, as illustrated in Fig. 7.

Observations on reliability suggest that a meter that has passed preliminary inspection should be run in for a few hours at a variety of positive and negative velocities, and then calibrated at least four times, preferably over an interval of several days. If all calibrations consistently show an e_p of a single observation of less than 0.3% of C_m , the meter is usable. Good meters will show an e_p on the same order as that of the calibration facility; this was the case for 90 percent of the calibrations reported on here. Only calibrations in liquid hydrogen can establish reliability and probable accuracy.

The cleanliness, fit, and alignment of bearings is considered most important. This fact should dominate the packaging, storage, repair, and handling of any meter.

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21. A. J. Szaniszlo and L. N. Krause, "Simulation of Liquid-Hydrogen Turbine-Type Flowmeter Calibrations Using High-Pressure Gas", NASA TN D-3773 (1966)^a.

^aObtainable from National Technical Information Service, Springfield, Virginia 22151

Table I. Test-Meter Characteristics

Model designation	A	Bd	E	F
Size, cm	4	4	2.5	2.5
Number of blades ₂	6	6	3	6
Area of pipe, cm ²	9.50	9.50	3.83	3.83
Area of annulus, cm ²	6.72	7.73	3.15	3.15
Blade-tip clearance, mm	1.30	0.50	0.43	0.32
Speed at ~10 m/sec, rpm	8000	6000	6000	6000

Table II. Number of Calibrations

Meter type	Bearing type	Number of meters	Total number of tests	Average tests per meter ^b
A	F	3	12	4
A	J ^a	3	50	2-13
Bd	R	1	15	15
E	R	4	29	7
F	R	6	30	5
F	F	4	20	5

^aDistributed among four materials

^bAverage test duration 2 h

Table III. Average value of $|\Delta C_m|_{\max}/C_m$ for Various Types of Meters

Meter type ^a	A-F	A-J	Bd-R	E-R	F-R	F-F
$ \Delta C_m _{\max}/C_m$, percent	0.4 ₁	0.3 ₆	0.06	0.2 ₁	0.1 ₃	0.1 ₈

^aPrefix - geometric design; suffix - type of bearing

Table IV. Pressure Drop at Various Fluid Velocities

Meter type	Pressure drop		Rotational speed, rpm	Velocity, ^a m/sec
	N/cm ²	psi		
A	5.0	7.3	22 000	27
	3.5	5.1	18 000	22
	1.4	2.0	11 000	14
	.4	.5	6 000 ^b	7
Bd	5.0	7.3	15 000	27
	3.5	5.1	13 000	22
	1.4	2.0	8 000	14
	.8	1.1	6 000 ^b	10
E,F	5.0	7.3	24 000 ^b	41
	3.5	5.1	20 000	34
	1.4	2.0	12 500	22

^aMean linear velocity in unobstructed upstream pipe

^bNominal full-scale speed

Table V. Properties of Fluids Used for Simulation

	Density, g/cm ³	Kinematic viscosity, stokes
H ₂ O at 300K, 1 bar	1.00	0.0117
LH ₂ at 20K, 1 bar	.071	.0019
GN ₂ at 300K, 63 bar	.071	.0028
GN ₂ at 300K, 82 bar	.103	.0019

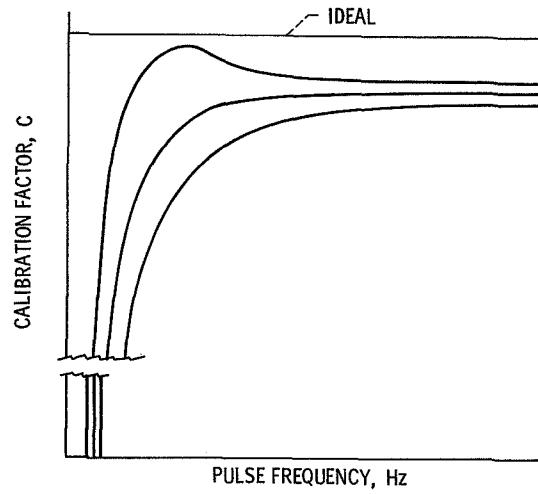


Figure 1. - Shapes of the calibration curve. Only the lowest and uppermost portions are shown. Separation of horizontal asymptotes is exaggerated for clarity.

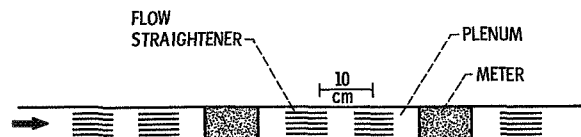


Figure 2. - Arrangement of test meters. Scale applies to 2,5-cm size. The transverse scale is exaggerated for clarity.

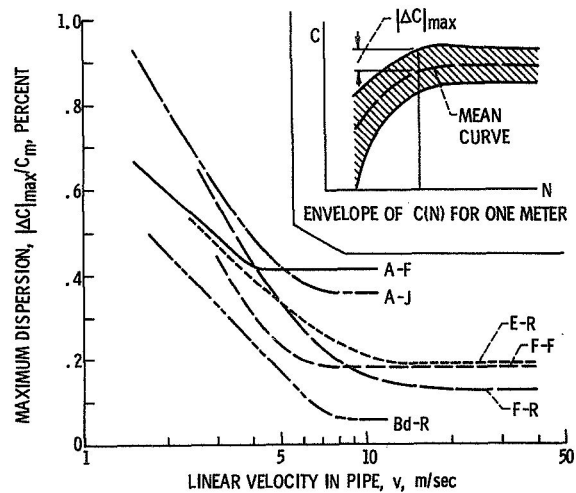


Figure 3. - Dispersion of the calibration factor for a single meter. The probable error is one half the ordinate value.

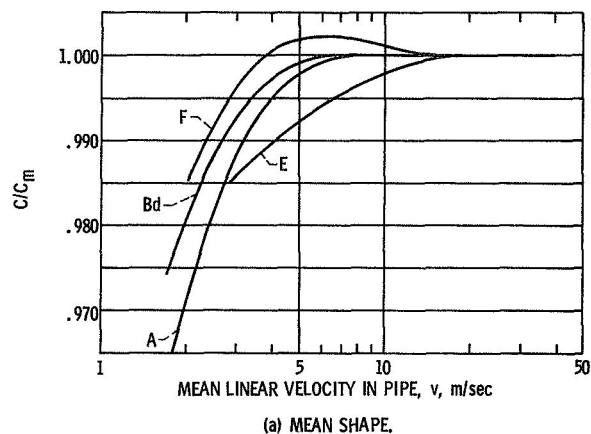
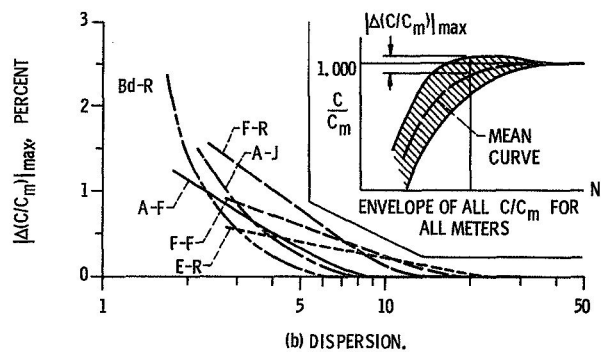


Figure 4. - Mean calibration-curve shape for various types of meters, and its maximum dispersion. The probable error is one half the ordinate value of figure 4(b).

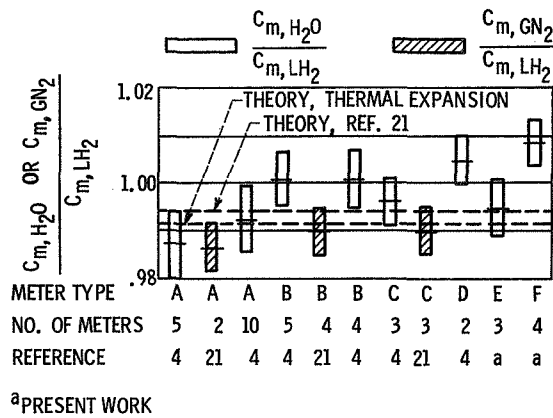


Figure 5. - Ratio of C_m in water or high-pressure nitrogen to C_m in liquid hydrogen, for various meter types.

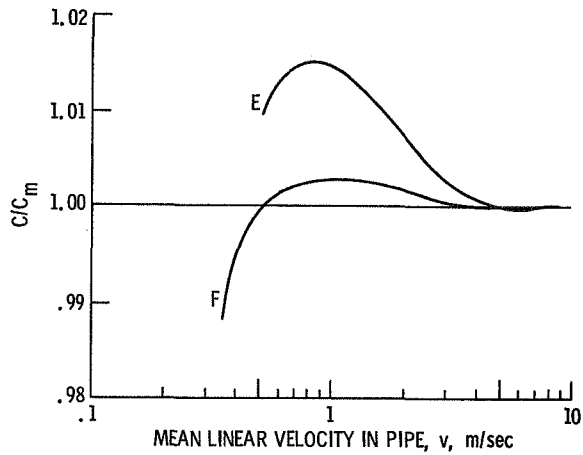


Figure 6. - Water calibrations for two meter types.

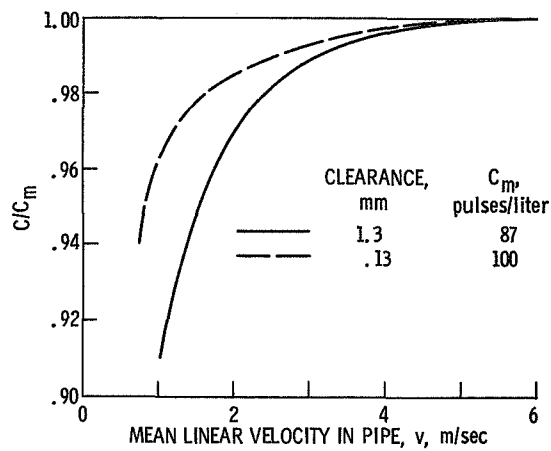


Figure 7. - Effect of blade-tip clearance on calibration-curve shape.